MANUFACTURING

ACCELERATING THE INCORPORATION OF MATERIALS ADVANCES INTO MANUFACTURING PROCESSES

Technology Innovation Program
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The Technology Innovation Program (TIP) at the National Institute of Standards and Technology (NIST) was established for the purpose of assisting United States businesses and institutions of higher education or other organizations, such as national laboratories and nonprofit research institutions, to support, promote, and accelerate innovation in the U.S. through high-risk, high-reward research in areas of critical national need.

TIP seeks to support accelerating high-risk, transformative research targeted to address key societal challenges. Funding selections will be merit-based and may be provided to industry (small and medium-sized businesses), universities, and consortia. The primary mechanism for this support is cost-shared cooperative agreements awarded on the basis of merit competitions.

AN AREA OF CRITICAL NATIONAL NEED

The proposed topic "*Accelerating the Incorporation of Materials Advances into Manufacturing Processes*" is within the Critical National Need area of Manufacturing. This topic was selected from a larger set of challenges in manufacturing where transformative research could be expected to have large societal impact. Input regarding potential challenges in manufacturing was obtained from government agencies and advisory bodies (such as the National Research Council, the National Academy of Sciences, and the National Academy of Engineering), the Science and Technology Policy Institute (STPI), industry organizations, leading researchers from academic institutions, and others.

Materials performance is often a critical consideration and controlling factor in the innovation process.[1] For example, high strength alloys, aluminum, and magnesium are used to build stronger, lighter and safer vehicles; superalloys are used to make higher efficiency gas turbines; composites make larger, more efficient wind turbine blades and provide improved performance in aerospace applications; and nanomaterials are finding their way into better performing batteries, energy storage devices, high voltage transmission lines and health care applications (e.g. imaging). Sustainable materials development and materials substitutions are additional examples where greater capabilities are critical to ongoing or increased competitiveness of U.S innovations.

Without the ability to produce these new materials and to rapidly integrate them into products while maintaining the material's unique properties, the U.S. will lose these value-added manufacturing innovations to overseas competition, a trend which has already occurred in so many industries.[2] This white paper outlines an opportunity to address two key areas related to the manufacturability of materials and products, and describes the supporting technical challenges that need to be addressed.

If successful, the manufacturing solutions envisioned would have the potential to ***create significant performance improvements in new products by accelerating the utilization of an advanced material's new functionality.***

MAGNITUDE OF THE PROBLEM

Manufacturing has a rich history and has long been a significant part of the American economy. The U.S. is the world's leading producer of manufactured goods. Standing alone, the 2002 manufacturing sector represented the fifth-largest economy in the world—larger than China's economy as a whole.[3] However, by 2007, the sector had fallen to eighth place, exceeding Spain's total economy.[4] The 2007 manufacturing sector represented 11.7 percent of the total GDP ($1,615.8 billion out of $13,841.3 billion total)[5] and supported 14 million jobs, or about 10.1 percent of the total U.S. employment. The sector also leads in innovation, accounting for more than 90 percent of all U.S. patents registered annually.[6] Transformative research often achieves broad national impact only through incorporation into manufactured products. To preserve this element of our economy, the manufacturing sector will need to continue to implement technology advancements in the coming years.

One technological need of manufacturing that crosscuts many of the proposed solutions to today's challenges involves materials advances and how to effectively and efficiently manufacture new materials (also referred to as manufacturability). For example, there are proposals for using nanomaterials to make high voltage transmission wires that behave in a similar way to room temperature superconductors; new composites to produce larger, more efficient wind turbine blades and new alloys to reduce vehicle weight (and thus increase fuel efficiency). The increasing demand for these ultra-high performance materials in production quantities at competitive costs spans many industries: aerospace, automotive, energy, mining and construction, electronics, defense, and even consumer goods. These materials challenges have been identified in various industrial road maps as well as white papers submitted to TIP. Examples of the problems and promises of advanced materials by broad material types include:

- Nanomaterials:[7,8,9,10,11]
  - Cost of manufacturing carbon nanotubes is a barrier to widespread use in products;
  - Control and measurement of feature size will lead to enhanced materials properties and device functions not currently foreseen (or even considered feasible);
  - Robust and reliable production methods with correct control and measurement for consistent features and no waste at the atomic scale are needed for consistent features and no waste;
  - Development of new instrumentation and measurements for real time process control and measurement are needed;
  - Byproducts, wastes, and impurities associated with manufacturing hinder acceptance and adoption in commercial applications; and
  - Scalable, cost-effective manufacturing of newly discovered materials is needed.

- Composite materials:[12,13,14]
  - Aerospace industry's emphasis on fuel efficiency favors the use of polymer-matrix composites instead of aluminum;

  - Automotive industry recognizes advantages of weight reduction, parts consolidation and increased cost-effective design options for polymer-matrix composites;
  - Energy sector's growing use of wind energy has led to increased demand for polymer-matrix composite turbine blades;
  - Better processes and tools needed to recognize special properties such as the anisotropic nature of these materials (strength and stiffness greatest in direction parallel to axis of the embedded reinforcements);
  - Need to overcome cost barriers to use such as expensive starting materials, time-consuming fabrication processes, and autoclaves and expensive tooling;
  - Multiple industries require accommodation of production of large, structurally complex parts; and
  - Increased application of recyclable composites can reduce carbon footprint.

- Alloys (Super, specialty,[15] aluminum, magnesium, titanium,[16] smart materials):
  - Performance advantages from novel metallic alloys could displace other materials in a variety of structural applications (i.e., defense, transportation, energy, electronics and process industries);
  - Performance, processing and cost continue to limit commercial viability;
  - Major barriers to widespread use of smart (alloy) materials[17] include the need for low-cost, robust and reliable production processes, and improved design tools to enable non-experts to use the materials with confidence; and
  - Smart (alloy) materials hold out promise of combining sensor capabilities in coatings for use in a wide variety of applications.

For the remainder of this paper, "advanced materials" will refer to materials that have unique functionalities but require improved controls and measurements to achieve desired functionalities in a revolutionary and cost-effective way. The unique functionality that these materials could bring to new products will require new levels of understanding in the sciences of materials processing and process control. For example, in nanomaterials, manipulation and measurement at the atomic level will be needed. In alloys, the control and measurement would be at the microscale (and eventually at the nanoscale) with an emphasis on anisotropic features of the micro (nano) structure. In composites, control and measurement would be at the mesoscale and would take advantage of the anisotropic layering of the process. Control of one material or phase within another will also be an important consideration.

Clearly there are additional classes of materials (e.g., polymers, ceramics, etc.) that could be included in this discussion. However, the three classes of materials described above are considered to be most critical to emerging or other potential growth areas for manufacturing.

MAPPING TO NATIONAL OBJECTIVES

There is a long history of recognition of the need for a government investment in manufacturing and advanced materials as National priorities. The current administration has called for investments in compelling advanced manufacturing strategies[18] and for support of small- and mid-size manufacturers to produce innovative new technologies.[19] In *Rising above the Gathering Storm,*[20] the National Academy identified developments in metal alloys and composite materials for aerospace applications; and high performance materials such as superalloys, steel and aluminum alloys, titanium, superconductors, and others as being of critical importance to the economic future of the Nation.

Numerous other organizations have also developed technology roadmaps for advanced materials and their processing. Groups as diverse as the National Science and Technology Council (NSTC),[21,22] the Department of Energy's Industrial Technologies Program,[23,24] and the Aluminum[25] and Steel[26,27] Associations have all produced outputs relative to this technical area. These roadmaps, from a wide range of public and private sources, demonstrate the fundamental need for widely available, affordable new materials to meet a broad range of challenges. The preponderance of recent international roadmaps relative to U.S developed efforts is yet another indication of risk the U.S. faces in maintaining a leadership role in advanced materials and their manufacturability.

NIST Laboratory Activities

NIST is involved in a number of activities that support advanced materials development and processing.

- In NIST's three year programmatic plan, the discussion of an R&D Investment Framework cites advanced materials as one research area for consideration because it is among the most strategic and enables other rapidly developing technologies.[28]
- NIST's Materials Science and Engineering Laboratory (MSEL) is one of the world's premier institutions for materials-related measurement science. Over 300 research staff in MSEL creates the measurements, standards and data needed to advance the development of innovative metals, ceramics, polymers, nanomaterials and electronics materials that are key to National needs, including energy, healthcare, infrastructure, manufacturing and the environment. [29] Additional efforts in support of advanced materials are also supported by other laboratories at NIST, such as composites-related activities within the Building and Fire Research Laboratory (BFRL).[30]
- NIST's *Assessment of the U.S. Measurement System*[31] included the following key findings in the materials area:
  - A principal measurement problem in the materials sector/technology area is the absence of measurement instruments and methods capable of accurately characterizing the composition and the behavior of complex materials systems and structures; and
  - In the materials sector/technology area, a key factor driving the need for measurement innovation is the anticipated need to evaluate the performance and reliability of new materials successively at the production and market stages of their development. The timely delivery of measurement solutions in the materials sector/technology area is increasingly challenged by the growing complexity of materials systems and structures and their interfaces.

NIST's involvement in these activities and stated directions in the materials area further highlights the importance of accelerating utilization of advances in materials with novel properties.

MEETING A TIMELY NEED NOT MET BY OTHERS

The manufacturing community has not fared well for some time under the current economic climate and thus they do not have the capital to develop new high-risk, high-reward technology on their own. The National Science Foundation (NSF), Department of Energy (DOE) and other agencies generally fund basic materials discovery. No Federal agency has a lead responsibility to support research in the manufacture of these newly developed materials. An analysis of the funding gaps for recent appropriations, budgets and Federal Funding Opportunities shows there is a need to fund:

- New processes for scale-up from small scale laboratory materials ("bench top" efforts) while assuring composition and functionality;
- New processes that rapidly incorporate the functionality of new material developments into new products that exhibit revolutionary performance; and
- New predictive modeling capabilities to characterize the behavior of a new material's functionality and the effect of materials processing on material properties, and then application of such knowledge in manufacturing processes and final product design.

TIP, in supporting a topic such as *Accelerating the Integration of Materials Advances into Manufacturing Processes,* would be supporting a timely need that is not currently being met by others within the critical national need area of manufacturing.

SOCIETAL CHALLENGES

Manufacturing, like so many other areas of critical national need, has a variety of challenges that need to be addressed. There are challenges associated with agile[32] or intelligent[33] manufacturing, supply-side management,[34] sustainable manufacturing processes, specific manufacturing processes,[35,36] training, and a host of others. Analysis of current funding needs and consideration of an investment strategy that could benefit the broadest range of manufacturers suggests that there are two important challenges: 1) *Process scale-up, integration, and design for advanced materials*; and 2) *Predictive modeling for advanced materials and materials processing*.

1. **Process scale-up, integration, and design for advanced materials.**
   New materials typically are developed in a laboratory setting, and then samples are given to end-users for alpha and beta testing. During this testing phase, it can take considerable time and experimentation to understand how the material can be incorporated into a new product in a way that maintains and utilizes its unique functionality. Scaling-up from laboratory quantities to larger volumes, integrating these processes together, and then incorporating them into product manufacturing lines is often non-linear and does not follow straightforward scaling laws, due to the unique functionality that has been designed into the advanced material.

2. **Predictive modeling for advanced materials and materials processing.**
   Predictive modeling capabilities are key to developing new processes, scaling-up these processes and understanding how to utilize an advanced material's unique

functionality. Modeling capabilities are needed principally to:

a. Analyze and understand why a newly discovered material does what it does and then extrapolate its behavior to new conditions; and
b. Incorporate this knowledge into process design tools so new products can quickly be made while maintaining the unique functionality of the materials.

Environmental, Health and Safety (EHS) issues are an important consideration for both challenges. In order to be competitive in a global economy, products and processes must be designed to support good EHS practices. While TIP is not considering a specific challenge in EHS at this time, one would expect a solution for either or both proposed challenges to include key EHS concepts.

RELATIONSHIP OF SOCIETAL CHALLENGES WITHIN MANUFACTURING

To successfully address the proposed challenges for *"Accelerating the Integration of Materials Advances into Manufacturing Processes,"* research in new technologies will be needed. The table below illustrates the relationship between key challenges. The three columns of material types (nanomaterials, superalloys and composites) are arranged in order of increasing microstructural size. TIP would expect solutions to the challenges to map into one or more of the cells in the table.

Technological Needs		Nanomaterials	Superalloys, Alloys & Smart Materials	Composites
Processing of Materials	**Scale-up from Laboratory Quantities / Controls**			
	Incorporate into New Uses / Maintain Functionality			
Predictive Modeling	**Rules / Understand Why It Does What It Does**			
	Process Modeling / Design & Product Design Tools			

For the first challenge, ***process scale-up integration and design for advanced materials***, new processes will need to be developed. These processes will increase to commercial scale the quantity and quality of available advanced materials; or help incorporate these advanced materials into new, revolutionary products based on a new material's properties. These scaled-up processes may be a next generation or an entirely new process. For example, forging ever larger parts cannot be solved by building ever larger forges (which become prohibitively expensive), but instead by new partial forging techniques.

In support of these new processes, new instrumentation and measurement capabilities will also be needed. These instruments will need to measure real time process parameters such as the properties that provide the unique capabilities of the advanced materials (e.g., composition). In addition, instruments for real time inspection are needed to ensure and/or verify materials are being correctly incorporated into manufactured products that require the revolutionary functions of these new materials.

For the second challenge, ***predictive modeling for advanced materials and materials processing***, new tools are needed to enable researchers to use constitutive relations and rules (with validation) concerning the underlying behavior of materials (understanding structure vs. function) and the changes to behavior due to manufacturing processes. For example, new tools will need to account for the scale-dependent behavior of advanced materials. This capability will enable a better and quicker understanding of why materials do what they do. These efforts will also enable extrapolation of that knowledge beyond the laboratory conditions for which they were developed, and therefore will need new validation and verification capabilities.

In addition, critical knowledge is also needed about why certain decisions or assumptions were made in order to incorporate new modeling capabilities for laboratory results into process design and modeling. Again, new validation and verification methodologies will be essential.

With successful development of these tools, processes, and technologies, the manufacturing communities will have significantly improved capabilities to quickly incorporate advanced material breakthroughs into revolutionary products based on new material functionality, and thus establish new competitive advantages in a global economy.

An additional key characteristic to address is how the outcomes of the research will enable manufacturers to produce advanced materials faster, better and cheaper, as well as the new uses for the advanced material.

ANALYSIS OF COMMITMENT

Potential participants, including small- and medium-sized companies, universities, national laboratories and other organizations, have indicated interest in the challenge areas, and have the capabilities or relevant experience to:

- Develop laboratory-scale processes to make small quantities or test runs of materials;
- Develop and validate predictive modeling tools that analyze and help to understand why new materials do what they do;
- Develop and validate predictive modeling tools used in process design and development for new uses of advanced materials; and
- Develop new manufacturing processes that incorporate advanced materials into new uses.

As further evidence of commitment, TIP has received a number of white papers directly related to the manufacturability of materials.

SUMMARY

The manufacturing sector is being especially hard hit in the current economic climate. They are having greater difficulty than in the past finding the capital necessary to develop new technological capabilities to enhance their competitiveness. Several gaps in funding have been identified that are not currently being addressed, but if addressed, could provide the manufacturing sector with new and needed capabilities to address "*Accelerating the*

Integration of Materials Advances into Manufacturing Processes." Two challenges need to be addressed: 1) process scale-up integration and design for advanced materials and 2) predictive modeling for advanced materials and materials processing. The results of these efforts are expected to be revolutionary uses of advanced materials based on new material functionality that will benefit the manufacturing sector and the U.S.

Those seeking further information should consult the Federal Funding Opportunity notice.

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